Observing the Earth as an exoplanet with LOUPE, the Lunar Observatory for Unresolved Polarimetry of Earth

Karalidi, T.[a,b], Stam, D.M.[a], Snik, F.[b], Bagnulo, S.[d], Sparks, W.B.[c], Keller, C.U.[b]

[a] *SRON Netherlands Institute for Space Research, The Netherlands*
[b] *Leiden Observatory, The Netherlands*
[c] *Space Telescope Science Institute, USA*
[d] *Armagh Observatory, UK*

Abstract

The detections of small, rocky exoplanets have surged in recent years and will likely continue to do so. To know whether a rocky exoplanet is habitable, we have to characterise its atmosphere and surface. A promising characterisation method for rocky exoplanets is direct detection using spectropolarimetry. This method will be based on single pixel signals, because spatially resolving exoplanets is impossible with current and near-future instruments. Well-tested retrieval algorithms are essential to interpret these single pixel signals in terms of atmospheric composition, cloud and surface coverage. Observations of Earth itself provide the obvious benchmark data for testing such algorithms. The observations should provide signals that are integrated over the Earth's disk, that capture day and night variations, and all phase angles. The Moon is a unique platform from where the Earth can be observed as an exoplanet, undisturbed, all of the time. Here, we present LOUPE, the Lunar Observatory for Unresolved Polarimetry of Earth, a small and robust spectropolarimeter to observe our Earth as an exoplanet.

Keywords:
Polarisation, Spectropolarimetry, Moon, Exoplanets, Earthshine

1. Introduction

Since the discovery of the first exoplanet [13], more than 700 exoplanets have been detected as of today. Even though most of these exoplanets are gas giants, in recent years the number of detected smaller mass planets has

surged [see e.g. 30]. Indeed, according to [3], about 62% of the Milky Way stars should have an Earth–like planet. A near-future detection of an Earth-sized exoplanet inside its star's habitable zone seems unevitable. Whether or not an Earth-sized planet in a habitable zone is actually habitable, depends strongly on the composition and structure of its atmosphere. As an example, the Venusian surface is about 500° hotter than expected from Venus' orbital distance and albedo, thanks to an extremely strong greenhouse effect in its thick CO_2 atmosphere. Hence, a characterisation of the planetary atmosphere will be needed to address a planet's habitability.

Currently, atmospheres of exoplanets are being characterised using the so–called *transit method* [see e.g. 1, 14]. This method is based on measurements of the wavelength dependendence of starlight that filters through the upper layers of the planetary atmosphere during the primary transit (when the planet passes in front of the star), or of the planetary flux just before or after the secondary eclipse (during which the planet passes behind its star). The transit method is mostly applied to gaseous planets that orbit close to their star. Earth-sized exoplanets in the habitable zone of their star are too small to yield measurable transits [8].

The best way to characterise the atmosphere and surface of an Earth-sized exoplanet, is through *direct detection*, using large ground–based telescopes such as the European Extremely Large Telescope (E-ELT) or space telescopes with diameters of a few meters. With direct detection the light of a planet is measured separately from the stellar light (except for some background starlight). But even if we observe an exoplanet with a direct detection, the planet itself will be unresolved, i.e. it will appear as a single pixel. If the planet resembles the Earth, this single pixel holds information on oceans and continents, coverage by vegetation, desert, and, for example, snow and ice, all overlaid by various types of patchy clouds.

Polarimetry promises to play an important role in exoplanet research both for exoplanet detection and characterisation. In particular, because the direct starlight is unpolarized, while the starlight that is reflected by a planet will usually be polarized, polarimetry can increase the planet–to–star contrast ratio by 3 to 4 orders of magnitude [11], thus facilitating the detection of an exoplanet that might otherwise be lost in the glare of its parent star. Additionally, as in the case of Solar System planets [see e.g. 5, 15], polarimetry will help the characterisation of planetary surfaces and atmospheres, because the polarisation of the reflected starlight is very sensitive to the physical properties of an atmosphere and surface. Combining flux with

polarimetric observations will also help to break retrieval degeneracies that flux–only measurements have [see e.g. 24, 10, 9]. Finally, while measuring the state of *linear* polarisation of reflected starlight helps to characterise a planetary atmosphere and surface, the degree of *circular* polarisation of this light appears to be an indicator for the existence of life on a planet, since circular polarisation, and in particular its wavelength dependence, is linked to homochirality of the complex molecules that are essential for life [21, 25].

To decipher future signals of directly detected Earth-like exoplanets, numerical models that can simulate single pixel signals of exoplanets with inhomogeneous atmospheres and surfaces, are essential. Such models are essential for the design and optimisation of telescope instruments and mission profiles (spectral bands, spectral resolution, integration times, revisiting times, etc.), and, once observations are available, they are a necessary tool to interpret the observations. There are a number of numerical models that are used to calculate signals of gaseous and terrestrial exoplanets, for reflected starlight and/or thermally emitted radiation [see e.g. 19, 4, 24, 28, 9]. In order to validate the results of such numerical models, it is important to compare them against observations. The obvious test–case for numerical models for Earth–like exoplanets, is Earth itself. To fully validate these models, we need observations of the Earth as if it were an exoplanet, hence single pixel observations that cover the diurnal rotations of the Earth, and all phases of the Earth. And, ideally, the observations should cover different seasons to record the changes in surface albedos and weather patterns.

An excellent location for performing such observations and for building a benchmark dataset is the lunar surface facing the Earth. From there, we can observe the whole disk of the Earth, all of the time, at all phase angles, throughout the year. As we will argue in more detail in Sect. 3, such observations cannot be achieved by e.g. combining observations of Low Earth Orbit (LEO) satellites. In this paper, we present LOUPE, the Lunar Observatory for Unresolved Polarimetry of Earth. LOUPE is a small and robust spectropolarimeter that measures the flux and state of polarization of sunlight that is reflected by the Earth e.g. from ESA's Lunar Lander.

This paper is structured as follows. In Sect. 2, we present calculated flux and polarisation spectra of a single pixel Earth. In Sect. 3, we summarize the advantages of observing the Earth from the moon. In Sect. 4, we describe the LOUPE instrument. Section 5, finally, contains the summary and our conclusions.

2. Flux and polarisation spectra of the Earth as an exoplanet

2.1. Flux and polarisation definitions

Sunlight that is reflected by a planet can be described by a flux vector $\pi\vec{F} = \pi[F, Q, U, V]$, with πF the total flux, πQ and πU the linearly polarised fluxes and πV the circularly polarised flux [see e.g. 6, 7, 24]. Each flux parameter depends on the wavelength λ, and has dimensions W $\mathrm{m}^{-2}\mathrm{m}^{-1}$. Linearly polarised fluxes πQ and πU are defined with respect to the plane through the center of the star, the planet and the observer [see also 9]. The degree of polarisation P of the reflected sunlight is defined as the ratio of the polarised flux to the total flux, thus $P = \sqrt{Q^2 + U^2 + V^2)}/F$. Specifically, the degree of linear polarisation is defined as $P_{\mathrm{L}} = \sqrt{Q^2 + U^2}/F$, and the degree of circular polarisation as $P_{\mathrm{C}} = V/F$.

2.2. Sample flux and linear polarisation signals of the Earth

Figure 1 shows numerically calculated total fluxes πF and degrees of linear polarisation P_{L} as functions of the wavelength λ. The Earth's phase angle, α, is 90° (from the moon, one would see a 'half' Earth). The spectra have been calculated using the radiative transfer algorithm described in [24], which assumes horizontally homogeneous model planets. We used four model planets, covered by sand, forest, ocean, or ice, combined with a cloud free or a completely cloudy atmosphere (composed of the model A cloud particles of [10]) with an optical thickness of 10 (at 0.55 μm) and located between about 3 and 4 km. The forest and ice surfaces are treated as Lambertian reflectors, with albedos taken from the ASTER library. The ocean surface is completely flat and black with a Fresnel reflecting interface on top. The bi-directional and polarized reflection by the sand surface is modeled using an optically thick ($\tau = 20$ at all λ) layer of dust particles [12], with a single scattering albedo chosen such that the albedo agrees with that measured from an airplane above the Sahara [2].

To model the spectra of the horizontally *inhomogeneous* Earth, we apply the weighted averages method [24] using the total and polarized flux spectra of the horizontally homogeneous model planets. In Fig. 1, we have chosen the weighting factors such that they represent a case in which Africa and Eurasia are on the centre of the planetary disk and a case in which the Pacific ocean is on the centre. For comparison, the latter case is also shown with a cloud layer. For the solar flux that is incident on the Earth, we assume a constant

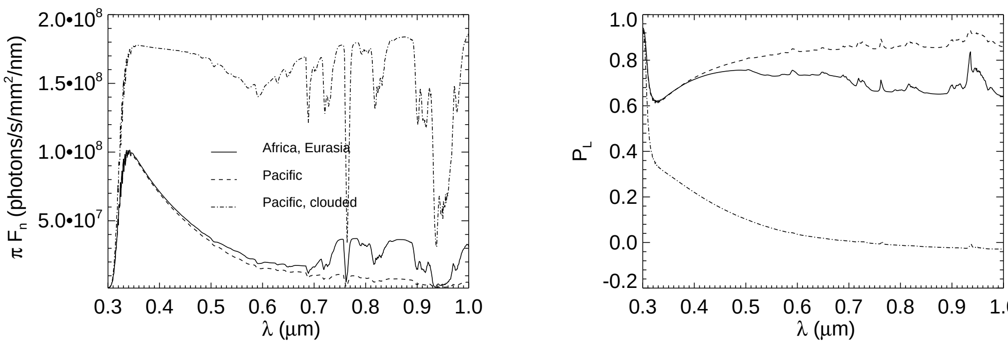

Figure 1: Calculated flux πF (left) and degree of linear polarisation P_{L} (right) of sunlight reflected by Earth as functions of λ, for $\alpha = 90°$: with Africa and Eurasia in view and no clouds (solid lines), with the Pacific ocean in view and no clouds (dashed lines) and when completely cloudy (dashed-dotted lines).

value throughout the whole spectrum equal to the solar flux (in photons s^{-1} mm^{-2} nm^{-1}) as measured by the GOME2 satellite instrument at 550 nm.

The flux and polarisation spectra of the cloud-free planets in Fig. 1 clearly show the traces of the Earth's surface and atmosphere. For a detailed explanation of the spectral features due to gaseous absorption by O_3, O_2, and H_2O, see [24]. Longwards of 0.7 μm, the characteristic red–edge albedo feature of the vegetation [18] clearly shows up in πF when the continents are in full view: πF is higher by almost a factor of 5 (at 0.85 μm) than when the Pacific is in view (a small fraction of this increase will be due to the sand surface). The red–edge feature shows up as a decrease of P_{L} (of about 20% in absolute value) because an increase in surface albedo increases the amount of unpolarized light that is reflected towards the observer. Adding clouds to the model atmosphere increases πF strongly (except in the deepest gaseous absorption bands): πF is $\sim$12 times ($\sim$ 23 times) higher at λ =0.65 μm (0.85 μm). At the same time, the clouds significantly decrease P_{L} at this phase angle ($\alpha = 90°$): $\sim$80% at λ =0.65μm. The model planets used in Fig. 1 are either cloudfree of completely cloudy. In reality, the Earth is only partly covered by clouds (with a range of optical thicknesses) and the real flux and polarisation spectra will be mixtures of the spectra that are shown here.

In Fig.2 we show πF and P_{L} at λ=550 nm, as functions of α for the model Earth that has a cloud coverage of about 42 % (the cloud properties

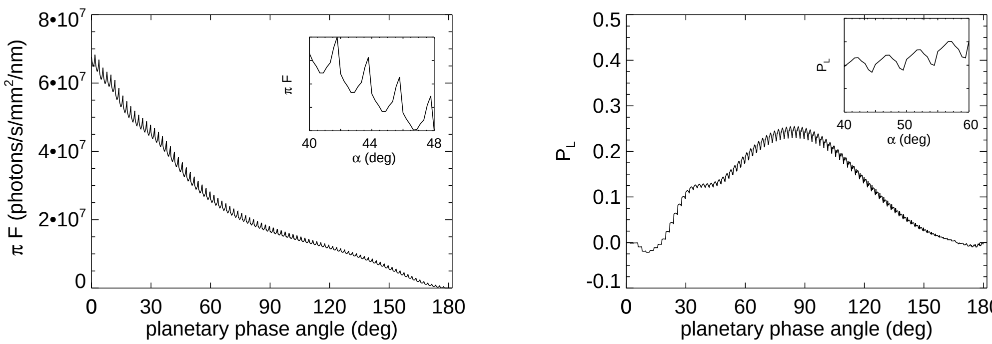

Figure 2: Calculated πF (left) and P_{L} (right) of sunlight reflected by a model Earth with 42% cloud coverage as functions of α, at 550 nm.

are the same as in Fig.1). The narrow features on top of the curves are due to the daily rotation of the planet as it orbits its star, showing ocean and/or continents through the holes in the clouds. The "bumps" in the curves around $\alpha = 30°$ are due to the primary rainbow: sunlight that has been scattered by the cloud droplets once. Clearly, the rainbow is much more pronounced in P_{L} than in πF. Finding a rainbow in exoplanetary polarisation signals will be a direct indication for the presence of liquid water droplets in the planetary atmosphere.

2.3. Circular Polarisation

All known living material on Earth exhibits homo–chirality: sugars and nucleic acids occur exclusively in the right–handed form, and amino-acids and proteins in the left-handed form. Homo–chirality makes light scattered by organic material partially circularly polarised, and circular polarimetric spectra of various samples of biological material have been published [31, 21, 25]. The reasons for homo–chirality are unknown, but if similar evolutionary scenarios naturally occur elsewhere in the universe, measuring P_{C} would be a unique tool for the detection of life on exoplanets. Since the Earth is the only planet we know that has life on it, Earth observations are the only way to empirically test this remote-sensing method. Some abiotic scattering processes (e.g. by optically active atmospheric aerosols or minerals) may also give a measurable P_{C}, but as shown in [21] the wavelength dependence of these signals is very different from that of the circular polarisation of biological material [22].

3. The advantages of using the Moon as observation platform

In order to build a comprehensive database of benchmark data of the Earth as an exoplanet and to be able to fully test numerical algorithms for signal simulation and planet characterisation, the requirements on the flux and polarisation observations are as follows:
1) Each observation of the Earth should be (nearly) instantaneous, to observe different regions on the illuminated and visible part of the Earth simultaneously and hence to capture the effects of the differences in local solar zenith angles and viewing angles.
2) Observations should cover the Earth's diurnal cycle, to capture the effects of different regions of the Earth emerging from the night, and disappearing over the limb (or the other way around), with the corresponding local changes in solar zenith and viewing angles.
3) The Earth should be observed at phase angles from $\sim 0°$ ('full Earth') to $\sim 180°$ ('new Earth'), with steps small enough to capture characteristic angular features in the reflected πF and P, such as the glint of sunlight reflected by surface water and the rainbow of sunlight scattered in clouds.
4) The observations should ideally cover all seasons to capture the effects of changes in local solar zenith angles, polar nights, weather and cloud patterns, and surface albedos.

Thanks to the monthly orbit of the Moon around the Earth and the tidal locking of the Moon with respect to the Earth, a spectropolarimeter on the lunar surface could observe the whole Earth, during each day, at all phase angles (depending on the power source), and, in principle, throughout the seasons. Such whole Earth observations *cannot* be obtained from (existing) artifical satellites, such as Low Earth Orbit (LEO) remote-sensing satellites or geostationary satellites.

LEO satellites observe local regions on the Earth, and would require several days to achieve global coverage. In addition, a certain location on Earth will always be observed under similar illumination and viewing geometries (apart for seasonal variations of the local solar zenith angle). Currently, only the POLDER Earth-observing satellite instrument has polarimetric capabilities (broadband, no spectropolarimetry). Geostationary satellites observe the same hemisphere of the Earth all of the time. While these satellites do capture the effects of the diurnal rotation and at the same time the phase angle changes of the Earth, they cannot observe different regions of the Earth, and their observations cannot teach us how to derive a global distribution of

oceans and continents from single pixel measurements. There are currently no polarimeters onboard any geostationary satellite.

Recent spectropolarimetric Earthshine observations [26], in which sunlight that has been reflected first by the Earth and then by the moon is measured with Earth-based instruments [see e.g. 17, 27] confirm that disk-integrated polarimetric observations are extremely sensitive to the visible surface and atmosphere of the Earth. At the same time, discrepancies between theoretical predictions and observations demonstrate that multi-epoch observations of the Earth are needed to constrain the models. The major drawback of Earthshine observations is that the properties of the lunar surface are not known well, especially when polarisation is involved. This makes the modelling enormously more difficult than in the case of observations from space (including the Moon). Ground-based Earthshine observations are also hampered by background contamination from the sunlit fraction of the Moon, and do not allow the same phase angle coverage (both in range and in angular resolution) and are unable to capture the full diurnal rotation.

Finally, a number of non–dedicated missions (e.g. Voyager 1, and more recently Deep Impact) have taken snapshots of the Earth.[1] These observations, while often providing interesting data, do not cover the diurnal rotation nor the phase angle range nor the seasonal effects. There have been no polarimetric observations performed by such missions.

A spectropolarimeter could be put onboard a specially designed satellite in an orbit that allows performing the required observations. That orbit would, however, probably closely resemble the orbit of the moon. Including the instrument on a Lunar Lander thus seems a straightfoward and economical choice.

4. LOUPE: the Lunar Observer for Unresolved Polarimetry of Earth

The Lunar Observatory for Unresolved Polarimetry of Earth (LOUPE) shall fulfill the following requirements:

- It performs spectropolarimetric observations of the light from the Earth's disk (at least) at visible wavelengths (400–800 nm).
- The spectral resolution for the polarimetry shall be ∼20 nm, while

[1]for a nice overview see: http://planetary.org/explore/topics/earth/spacecraft.html

the O_2A band ($\sim$0.76 μm) is resolved in the flux spectrum. Limited spectropolarimetry can be performed within this and other bands.

- Data is collected on an hourly basis to resolve the Earth's rotation, and span at least a month to cover a full range of phase angles.

- The instrument is small and robust.

For the polarimetry, we explore two different scenarios:
1) *Linear spectropolarimetry only.* For this we adopt the spectral modulation approach [20]. Using a combination of standard solid-state polarization optics (see Fig. 3), the total flux spectrum is multiplied by a sinusoidal modulation for which the amplitude scales with P_{L}, and the phase is determined by the angle of polarization. This novel polarimetric concept is being applied in the SPEX instruments. The SPEX prototype exhibits excellent polarimetric performance [29].
2) *Linear* and *circular spectropolarimetry.* This implementation is more challenging as the data dimensionality is larger, and, moreover, P_{C} ($\sim 10^{-4}$) is much smaller than the average P_{L} ($\sim 10^{-4}$ versus ~ 0.1). The spectral modulation approach in [16] yields three modulation periods that contain information on the complete flux vector. The modulation approach introduced by [23] yields similar modulations, but along the slit direction.

Various options can be identified for spatial resolution and pointing:
A) The instrument itself averages the light from the Earth's disk ($\sim 2^\circ$ diameter). Because the disk is surrounded by black space, this requires only course pointing. The acceptance angle of the instrument should be wide enough to take lunar libration ($\pm 8^\circ$) into account.
B) The instrument spatially resolves the Earth's disk to obtain data of e.g. just the Amazonian rainforest to maximize the circular polarization signal. Such spatial information can be attained by using a scanning slit or an integral field unit. In any case, accurate pointing and potentially scanning should be implemented. Averaging over the Earth's disk is then performed in the data pipeline.

A sketch of the most basic implementation (1A: only linear spectropolarimetry and no spatial resolution) of LOUPE is presented in Fig. 3.

5. Summary and conclusions

We present LOUPE, the Lunar Observatory for Unresolved Polarimetry of Earth. LOUPE is a small and robust spectropolarimeter that can observe

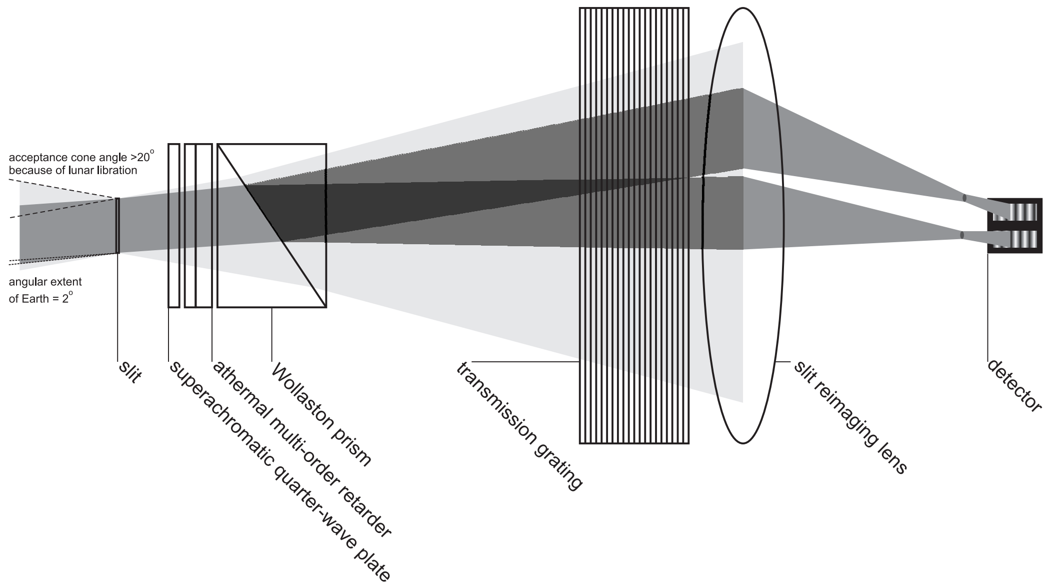

Figure 3: Schematic depiction of LOUPE option 1A (only linear spectropolarimetry, no spatial resolution) The scale is approximately 1:1. Such an instrument only needs to be roughly pointed towards the Earth as the instruments accepts light from all angles within the range determined by the lunar libration.

the Earth as if it were an exoplanet from a vantage point on the lunar surface. The Moon has a unique position with respect to Earth and can provide us with a unique platform from where we can observe the Earth as an exoplanet. From the Moon, LOUPE will be able to observe the whole disk of the Earth, all of the time, at most phase angles and throughout the year.

LOUPE measures the total flux and state (degree and direction) of polarisation of sunlight that is reflected by the Earth. Polarimetry appears to be a strong tool for the characterisation of exoplanets, allowing the retrieval of the composition and structure of a planet's atmosphere and surface (if present). In particular, the degree of linear polarisation can give us information on the presence of liquid water clouds and the degree of circular polarisation on the presence of life. LOUPE measurements would be used as a benchmark for future Earth-like exoplanet observations and to test numerical algorithms for the retrieval of planet properties from such observations.

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